

Review

Life Cycle Assessment and Material Flow Analysis: Two Under-Utilized Tools for Informing E-Waste Management

Sohani Vihanga Withanage * and Komal Habib

School of Environment, Enterprise and Development (SEED), University of Waterloo, 200 University Ave. W, Waterloo, ON N2L3G1, Canada; komal.habib@uwaterloo.ca

* Correspondence: svwithanage@uwaterloo.ca; Tel.: +1-226-792-2537

Abstract: The unprecedented technological development and economic growth over the past two decades has resulted in streams of rapidly growing electronic waste (e-waste) around the world. As the potential source of secondary raw materials including precious and critical materials, e-waste has recently gained significant attention across the board, ranging from governments and industry, to academia and civil society organizations. This paper aims to provide a comprehensive review of the last decade of e-waste literature followed by an in-depth analysis of the application of material flow analysis (MFA) and life cycle assessment (LCA), i.e., two less commonly used strategic tools to guide the relevant stakeholders in efficient management of e-waste. Through a keyword search on two main online search databases, Scopus and Web of Science, 1835 peer-reviewed publications were selected and subjected to a bibliographic network analysis to identify and visualize major research themes across the selected literature. The selected 1835 studies were classified into ten different categories based on research area, such as environmental and human health impacts, recycling and recovery technologies, associated social aspects, etc. With this selected literature in mind, the review process revealed the two least explored research areas over the past decade: MFA and LCA with 33 and 31 studies, respectively. A further in-depth analysis was conducted for these two areas regarding their application to various systems with numerous scopes and different stages of e-waste life cycle. The study provides a detailed discussion regarding their applicability, and highlights challenges and opportunities for further research.

Keywords: electronic waste; literature review; keyword co-occurrence network; material flow analysis; life cycle assessment



Citation: Withanage, S.V.; Habib, K. Life Cycle Assessment and Material Flow Analysis: Two Under-Utilized Tools for Informing E-Waste Management. *Sustainability* **2021**, *13*, 7939. <https://doi.org/10.3390/su13147939>

Academic Editor: Carlos A. Teixeira

Received: 11 June 2021

Accepted: 7 July 2021

Published: 16 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Electronic waste (e-waste) is one of the fastest growing waste streams in the world, making its management one of the greatest challenges we are facing today. It is sensible to argue that the drastic increase in the use of electrical and electronic equipment (EEE) along with the rapid technological advancements and economic development during the last two decades have resulted in the consequent escalation of end-of-life products, commonly referred to as e-waste [1]. In 2019 alone, approximately 53.6 million metric tons (Mt) of e-waste was generated globally, whereas only 17.4% of this was recycled properly [2]. Proper handling of e-waste and efficient recycling can enable the recovery of valuable raw-materials, which not only reduces the demand for finite primary resources, but also brings significant economic and environmental benefits [3]. Various authors have asserted that lack of reliable data on e-waste generation and incomplete knowledge on the material flows after end-of-life are major challenges for better management and material recovery from e-waste [1,4,5]. This systematic literature review provides a comprehensive overview of e-waste literature from 2010 to 2020 with the aim of understanding the applicability of strategic tools, such as material flow analysis (MFA), in e-waste research. This paper will first provide a brief background on e-waste, followed by the literature review methodology, results and discussion, and conclusions.

1.1. Electrical and Electronic Equipment and E-Waste

The electrical and electronic equipment (EEE) includes “a wide range of products with circuitry or electrical components with a power or battery supply” (Step Initiative, 2014; p. 4) [6]. EEE has become an integral part in the global economy due to the rapid rise in technological innovations and widespread global economic development [2,7]. Digitization of day-to-day operations along with the lowered costs and higher levels of disposable income have dramatically increased access to electronics, resulting in an exponential growth in usage [4]. It is reported that, on average, the total weight of electronics used in the world increases annually by 2.5 million Mt, which is dramatically high compared to the annual growth of the recycling rate of 0.4 Mt [2]. Increased consumption as well as shortened lifespans of electronics with quickly outdated technologies have paved way to an inevitable increase in their waste counterpart, e-waste.

Electronic waste, or e-waste, refers to “all items of electronic and electrical equipment and its parts that have been discarded by its owner as waste without the intent of re-use” (Step Initiative, 2014; p. 4). E-waste is also referred to as waste electronics, e-scrap, end-of-life (EoL) electronics, or more often as waste electrical and electronic equipment (WEEE). There is a large variety of EEE products on the market with different material compositions, functions, lifetimes, and end-of-life attributes, making it essential to have a sensible and practically useful categorization for grouping EEE [8]. The WEEE Directive [9], enforced in the European Union (EU) member countries, initially listed 10 categories for which data should be collected: (1) Large household appliances; (2) small household appliances; (3) IT and telecommunication equipment; (4) consumer equipment; (5) lighting equipment; (6) electrical and electronic tools; (7) toys, leisure, and sports equipment; (8) medical devices; (9) monitoring and control instruments; and (10) automatic dispensers. During the recast in 2018, the WEEE Directive listed the following six categories that should be reported from 15 August 2018, which is the categorization currently in use [2,8].

1. Temperature exchange equipment (cooling and freezing equipment)—includes refrigerators, freezers, air-conditioners, and heat pumps
2. Screens and monitors—includes televisions, computer monitors, laptops, notebooks and tablets
3. Lamps—includes florescent lamps, LED lamps and high intensity discharge lamps
4. Large equipment—includes washers, dryers, dishwashers, electric stoves, large printing and copying equipment, and photovoltaic panels
5. Small equipment—includes vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, electrical and electronic toys, and small medical devices
6. Small IT and telecommunication equipment—includes mobile phones, global positioning systems (GPS), pocket calculators, personal computers, printers, and telephones

Regardless of the differences in economic values, material composition, lifetime profiles, and waste quantities, all EEE is capable of generating severe environmental and human health impacts if recycled inappropriately [7].

1.2. Trends in Global E-Waste Generation

According to the ‘Global E-waste Monitor 2020’, which is the most recent source of e-waste estimations [2], approximately 53.6 million Mt of e-waste was generated in 2019 alone, which is equivalent to 7.3 kg per capital. The global quantity of e-waste is growing exponentially with a current increase in almost 2 Mt per year and it is estimated that the total generation will exceed 74 Mt in 2030. Although the rate of generation increases rapidly, the recycling rate of e-waste does not seem to increase fast enough to keep up. In 2019, only 17.4% (9.3 Mt) of e-waste was formally documented to be collected and properly recycled. Although it is an annual growth of about 0.4 Mt since 2014, it is significantly low compared to the global growth rate of e-waste which is 2 Mt annually. The lack of formal collection or recycling data on a large fraction of e-waste generated (82.6% in 2019) implies that this e-waste is likely dumped, traded, or recycled improperly. When the geographical distribution is considered, 54.8% of global e-waste was generated in Asia in 2019 which was

equal to 24.9 Mt. Interestingly, the highest per capita generation of e-waste was reported in Europe, with a value of 16.2 kg per capita [2].

1.3. Impacts Associated With E-Waste

Staggering amounts of e-waste is a critical issue today due to the associated long-lasting consequences it can have on both people and the planet. E-waste contains several hazardous and toxic substances including heavy metals such as cadmium (Cd), lead (Pb) and mercury (Hg), brominated flame retardants (BFR), chlorofluorocarbons (CFCs), polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls (PCBs) [10,11]. Artisanal or informal recycling (manual sorting, dismantling, and open burning of e-waste) without any safety precautions can lead to significant environmental pollution as well as serious human health implications [5,10]. For example, heavy metals and toxics leaching from e-waste due to improper landfilling or open burning can contaminate soil and ground water, creating persistent impacts on the ecosystem as well as on food chains [10,12,13]. Moreover, researchers have found that exposure to toxic substances from e-waste can create numerous health issues including but not limited to respiratory issues, thyroid malfunctions, changes in temperament and behavior, changes in cellular expression and function, adverse neonatal outcomes, infant mortality, and birth defects [12–14].

In addition to the environmental impacts upon disposal, e-waste also contributes to climate change due to their material and resource intensity during material extraction, production and even use. Electronics are comprised of a variety of scarce metals and rare earth elements (REEs), which are limited in supply and would generate notable environmental impacts during mining [11,15]. Nevertheless, manufacturing of electronics is associated with significant amounts of carbon emissions even before reaching the consumer [11]. Thus, improper management of e-waste can contribute significantly to global warming.

Despite regulatory efforts to control the transboundary movement, developed countries still export a large volume of e-waste into developing countries, such as China, Nigeria, Ghana, Philippines, and India [16]. More often than not, the workforce in the e-waste industry are comprised of marginalized and poor populations including immigrants, prisoners, women, and children. As the World Economic Forum (2019) reported, although the total number of people working informally in the global e-waste sector is unknown, it is estimated to be approximately 100,000 people in Nigeria and 690,000 people in China.

1.4. Opportunities for Material Recovery

In the perspective of material composition, up to 69 elements from the periodic table can be found in EEE, making the e-waste stream extremely complex [2]. While iron, aluminum, and copper account for the majority of the weight of raw materials found in WEEE, it also includes other precious metals (e.g., gold, silver, platinum, palladium, copper, rhodium, etc.) and critical raw materials (CRMs) (e.g., antimony, bismuth, cobalt, palladium, indium, and rare earth elements, etc.) [7,17]. According to global estimates for 2019, Forti et al. (2020) estimated the value of selected raw materials found in e-waste to be approximately 57 billion USD. Given that the global availability of raw materials is constantly under pressure due to increased demand in many industries, market price fluctuations, and environmental and human health issues related to primary extraction, e-waste could be considered an important source for the mining of secondary raw materials [17,18].

Access to CRMs has become a notable concern for governments and industry due to global supply constraint issues [19]. CRMs are the ones crucial for a system to function, such as technology, company, country, region, and the whole world. In the meantime, they are prone to potential supply risk [20]. Emerging technologies in the EEE industry, including thin layer photovoltaics, Li-ion batteries, permanent magnets, fiber optic cables, and micro-capacitors, pose a significant demand for CRMs. Moreover, some of the low carbon technologies, including wind turbines, also account for a considerable fraction of CRMs consumption, which is on the rise as nations attempt to meet their carbon emission reduction goals for the Paris Agreement [15,16,19,21].

As discussed in detail by Charles et al. (2020) and Habib (2015), availability of CRMs is more of a supply bottleneck issue rather than a global scarcity [19,22]. Many nations face CRMs supply issues only because most of CRMs production is concentrated in a smaller number of countries (e.g., China, Brazil, and South Africa). Thus, one important solution would be to consider material circularity to ensure products containing CRMs would retain within an economy through reuse, recycling, and material recovery [18–20]. In this aspect, WEEE becomes a lucrative source for the secondary supply of CRMs, opening significant opportunities and incentives for efficient managing and recycling.

1.5. Managing E-Waste

Effective and proper handling of e-waste is essential to minimize the associated environmental and human health impacts. Effective e-waste management should consist of proper collection and sorting, repairing and reusing whenever possible, end-of-life processing to remove toxic compounds, recovering of valuable materials, and safe disposal of toxic parts and non-recyclable residues [16]. Nevertheless, e-waste can be considered as an attractive resource base for urban mining since it contains a large variety of valuable materials, many of which are technically recoverable [7,23–27]. Due to precious metals such as gold, silver, platinum, and palladium, the resource perspective of secondary raw materials for e-waste was reported to be worth 55 billion euros in 2016 [7]. Recycling e-waste and recovering these valuable metals can reduce the burden for primary resource extraction through mining by catering to the global demand for scarce materials [4]. Although there is a remarkable potential for resource recovery, e-waste management is currently facing significant issues and challenges, making the e-waste problem an arduous one to resolve [16].

One of the most critical gaps associated with e-waste management is the lack of reliable data and statistics on the quantities of e-waste being generated [4,5,16]. Measuring and monitoring e-waste quantities on the national and international level is essential in addressing the e-waste challenge. Proper measurements and reliable data helps in tracking developments, setting and monitoring targets, identifying the best practices for policy implementation, preventing illegal dumping and improper handling, promoting recycling, and creating jobs in the reuse and recycling sectors [7,8]. Data on e-waste is relatively scarce in a majority of the countries, whereas harmonized statistics are currently available only for Europe [5]. The United Nations University (UNU) has developed comprehensive overviews of the global e-waste quantities in 2017 and 2020 [2,7], and have also published a guidelines document [8] on measuring e-waste. However, significant gaps in national-level e-waste stocks and flows still exist, both in developed and developing countries.

1.6. Tools for Assessing WEEE Generation, Management, and Associated Impacts

The complexity in WEEE management has prompted the need for suitable tools to understand the generation of e-waste as well as to assess the associated environmental impacts. Two such tools that are frequently used in waste management in general and also associated with WEEE are material flow analysis (MFA) and life cycle assessment (LCA). Both of these tools are frequently referred to in literature as useful in assisting decision-making in WEEE management [28,29].

Material flow analysis (MFA) is popular among many researchers around the world as a valuable tool to study and manage complex waste systems [29]. Specifically in resource management and waste management, MFA is considered to be an attractive decision support tool [30], since it is capable of studying the route of materials flowing into recycling sites and stocks of materials in space and time [29,31]. This tool can be applied to understand issues and gaps in the value chain and develop appropriate management strategies. It is especially beneficial for complex and distinct waste streams, such as e-waste, where the waste is comprised of both valuable and toxic materials [29,30,32].

LCA is an effective and popular environmental management tool that is capable of evaluating environmental impacts of a product or a service and can help to identify hotspots

and potential for improvement [33,34]. Several researchers have recommended LCA as a suitable tool to assess environmental impacts of waste management and also to compare the environmental performance of various waste management strategies including WEEE management [33,35–37]. Previous studies have also found that there is an increasing trend of LCA application in waste management research [34]. Two recent reviews by Xue & Xu (2017) and Ismail & Hamafiah (2019) focused on the application of LCA in e-waste literature published before 2018 [33,34].

1.7. Rationale and Objectives

The recent spotlight on e-waste has gained significant attention from researchers worldwide and has led to an increasingly rapid growth of related publications [38]. Thus, it is crucial to systematically analyze the available literature in order to understand the trends, major focus areas, methodologies, and research gaps. A number of reviews (e.g., [28,29,33,38,39]) related to WEEE management have been carried out to date, providing a wide range of information on the global trends of e-waste generation, associated environmental impacts, recycling and recovery aspects, etc. Most of these reviews focus on specific issues related to WEEE whereas a general overview of all WEEE literature is quite rare. One such comprehensive review was published by Pérez-Belis et al. (2015) [38], which provided an overview of e-waste literature published prior to 2015. However, research that was published within the last five years have not been captured comprehensively in any such review so far. With the increased global attention on resources and waste in general after the introduction of Sustainable Development Goals (SDGs) in 2015, it would be interesting to evaluate how the WEEE research has evolved over the last five years. Thus, the aim of this paper is to conduct an in-depth literature review on WEEE and to provide a panoramic view of the available literature to create a common framework of knowledge in this field. This paper aims at identifying the main areas of e-waste research, the countries, and methodologies. The current review also aims to delve deep into e-waste research that utilized MFA and LCA as strategic tools to understand their applicability and future research potential. In a previous review [33], Ismail & Hanafiah (2019) emphasized the need for further literature reviews on methodological aspects related to e-waste management, which further justifies the purpose of the current review. A recent review article by [39] discussed the research trends, geographical scope, and current research practices and applications in e-waste studies published from 2005 to 2019. The study used content analysis as a method, where the sample size was 130 studies. Compared to this, our study offers the most comprehensive review of e-waste research being conducted over the last decade (2010–present) with a starting sample size of 1835 studies. The present study is unique from previous literature reviews since it serves two distinct purposes; (a) provides a comprehensive overview of all e-waste literature over the last decade by identifying key research areas and gaps, and (b) provides an in-depth analysis of the application of MFA and LCA in e-waste research.

2. Materials and Methods

This systematic literature review is based on an extensive search in two selected research databases, Scopus and Web of Science, by using a keyword search. These two databases were selected for the literature search due to their size, coverage, and relevance in the subject field. Peer-reviewed journal articles published after 2010 that had the keywords “e-waste”, “electronic waste”, “Waste Electronic and Electrical Equipment”, “WEEE”, “End of life electronics”, “Waste electronics”, and “In use stocks of electronics” in the title were filtered out from both databases. Since the selected keywords covered all possible uses of ‘e-waste’, it was assumed that, if a study was mainly focused on e-waste, one of these keywords must appear in their title. Web of Science identified 1478 articles whereas Scopus identified 1824 studies. After removing the duplicates, 1835 peer-reviewed journal articles were selected for the desk review. This step-by-step filtering process is summarized in Figure 1. The selected 1835 studies were first projected to a bibliographic network analysis

for understanding the most and least frequently researched areas in WEEE literature. Secondly, a more in-depth review was conducted to explore the application of MFA and LCA in WEEE research.

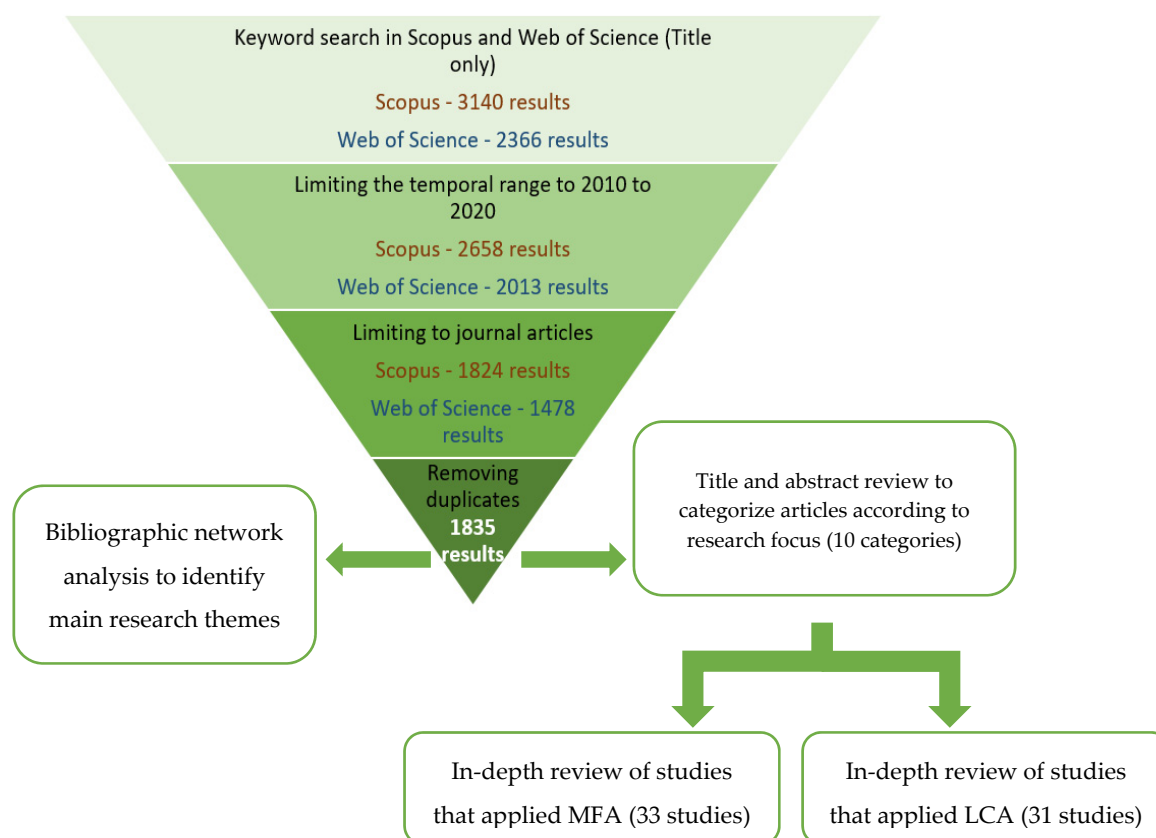


Figure 1. Summary of the literature review methodology.

2.1. Bibliographic Network Analysis

Bibliographic network analysis, also known as Systematic Literature Network Analysis (SLNA), is a novel literature review methodology that is used to objectively explore how previous research has addressed specific subject areas over time based on quantitative measurements [40]. This method complements the traditional qualitative literature reviews based on content analysis by providing an objective synthesis and a clear visualization of the development of a research area over time in a rigorous manner [41]. Previous studies (e.g., [40,41]) have conducted SLNA using numerous tools such as citation network analysis, global citation co-analysis, and keywords co-occurrence network analysis. In the present study, a keyword co-occurrence network analysis was conducted using VOSviewer (version 1.6.16) software [42] to analyze bibliographic data from the selected 1835 studies and visualize the most recurring keywords and their co-occurrence in e-waste literature.

2.2. In-Depth Desk Review

The selected 1835 research articles were subjected to a detailed qualitative desk review following the above bibliographic network analysis to further understand the focal research areas in WEEE literature. Firstly, with careful screening of the titles and abstracts, these articles were categorized into 10 broad research areas according to the research objective of each study: (1) environmental and human health impacts; (2) recycling and recovery technologies; (3) e-waste generation estimates and general management; (4) policy and regulations; (5) material/chemical characterization; (6) social aspects; (7) material flow analysis; (8) life cycle assessment; (9) circular economy; and, (10) other. It should be noted that there were overlaps in the research objectives in some studies where one could argue

they belong in more than one category. In such instances, one category was selected based on the purpose statement of the study to avoid double counting. Secondly, the research articles that have used MFA or LCA as a strategic tool (Categories 7 and 8 above) were selected for further in-depth review given that MFA and LCA are two most popular tools in quantifying actual environmental impacts of specific products or processes in a systems perspective.

3. Results

Bibliographic analysis of the selected 1835 articles shows how the number of publications related to WEEE has increased steadily over the last decade (Figure 2). According to the results, the number of research articles has almost doubled from 2015 to 2020, which further justifies the need of the current review, which captures the more recent studies that were not included in the previous reviews.

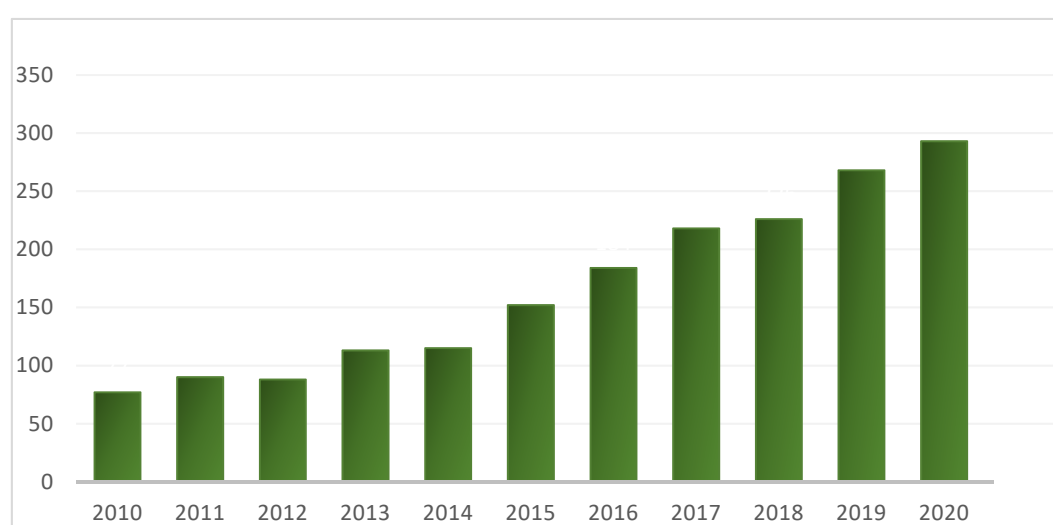


Figure 2. Number of research publications related to WEEE from 2010 to Jan 2020.

The top five academic journals ranked in order of number of publications were *Waste Management* (126 articles), *Science of the Total Environment* (97 articles), *Journal of Cleaner Production* (89 articles), *Environmental Science and Pollution Research* (79 articles), and *Resources, Conservation and Recycling* (71 articles).

3.1. Prominent Branches of E-Waste Research

Keyword co-occurrence networks are used to gather insights about major research themes within a knowledge domain by identifying the most recurring keywords in publications [43]. The present study used VOSviewer software [42] to visualize the co-occurrence of author keywords in the selected 1835 journal articles related to e-waste. From a total of 3918 author keywords extracted from 1835 journal articles, keywords which occurred at least ten times were considered for the keyword analysis. Accordingly, 84 keywords met this criterion. Thereafter, keywords that solely meant ‘e-waste’ (e.g., WEEE, electronic waste, waste electronics, etc.) were deliberately excluded since all selected articles were focused on e-waste. A thesaurus file (a separate file that is used to clean data by merging words with similar meanings, abbreviated terms, and excluding selected words/phrases) was used to further clean the keywords and avoid repetition due to acronyms and scientific notation. This reduced the total number of keywords included in the analysis to 73.

A keyword map generated from the present analysis is shown in Figure 3. The size of the node indicates the frequency of occurrence while the distance and links between nodes represent the relatedness and the number of times the keywords appear together. In addition, the analysis identifies distinct clusters comparing the co-occurrence of the

keywords. Present analysis revealed that the most frequently occurring keyword in the last decade of e-waste literature is ‘recycling’ with 224 occurrences, followed by ‘heavy metals’, ‘pbdes’ (polybrominated diphenyl ethers), ‘pcbs’ (polychlorinated biphenyls), and ‘soil’, indicating that the majority of the e-waste literature may revolve around recycling and toxic chemicals. Clustering algorithm in the VOSviewer software generated four distinct clusters after grouping the smaller clusters together.

The biggest cluster is the one that is shown in red in Figure 3, with 29 items containing keywords related to environmental and human health exposure, mostly due to toxic chemicals found in e-waste (e.g., heavy metals, PCBs, PBDEs, soil, lead, human exposure, dust, etc.). This indicates that a larger proportion of e-waste literature concerns the negative health and environmental impacts associated with e-waste. The second largest cluster contains 15 items and is shown in green (Figure 3, middle left) in the keyword map. In addition to the keyword ‘recycling’ which is centered in this cluster but connected to all other clusters, a few other keywords such as ‘circular economy’, ‘waste management’, ‘reverse logistics’, ‘life-cycle assessment’, and ‘material flow analysis’ take prominence in this cluster. This second cluster appears to represent research that links the recycling of e-waste to the industrial ecology aspects, such as MFA and LCA. Moreover, the circular economy, which has recently received a lot of momentum across governments, industry, and academia, is appearing as a distinct node in this cluster. When the network map was adjusted to illustrate the temporal distribution, it was distinctively observed that the circular economy has appeared in e-waste research only over the last few years, and also that a larger fraction of the most recent publications on e-waste has been related to the circular economy (e.g., [19,31,44–49]). This indicates that, similarly to the growth of circular economy research in general, its application in e-waste is also on the rise. The third cluster shown in blue (bottom left) includes literature related to e-waste management in general, consisting of keywords ‘sustainability’, ‘e-waste management’, ‘informal sector’, ‘China’, ‘India’, and ‘legislations’. The fourth cluster shown in yellow (top) contains keywords related to material recovery, indicating that the recovery of precious metals and rare earth elements using technologies such as bioleaching and hydrometallurgy is also an emerging branch of research in e-waste literature. Thus, to summarize, this analysis has identified four main branches of research in e-waste literature, namely, environmental and human health implications, general management of e-waste and related policies, recycling and reuse for material circularity, and recovery of precious metals and REEs.

It was observed that four countries, China, India, Ghana, and Vietnam, emerged as nodes in the keyword map, indicating that a notable fraction of e-waste research was based on these countries. Moreover, while the heavy metals cadmium and lead have gained individual attention possibly due to their toxic characteristics, gold has emerged among precious metals, suggesting a heightened attention relating to the recovery of gold from WEEE. In addition, two industrial ecology tools, LCA and MFA, have also appeared as prominent nodes in the recycling cluster, indicating a frequent application of these tools in e-waste research.

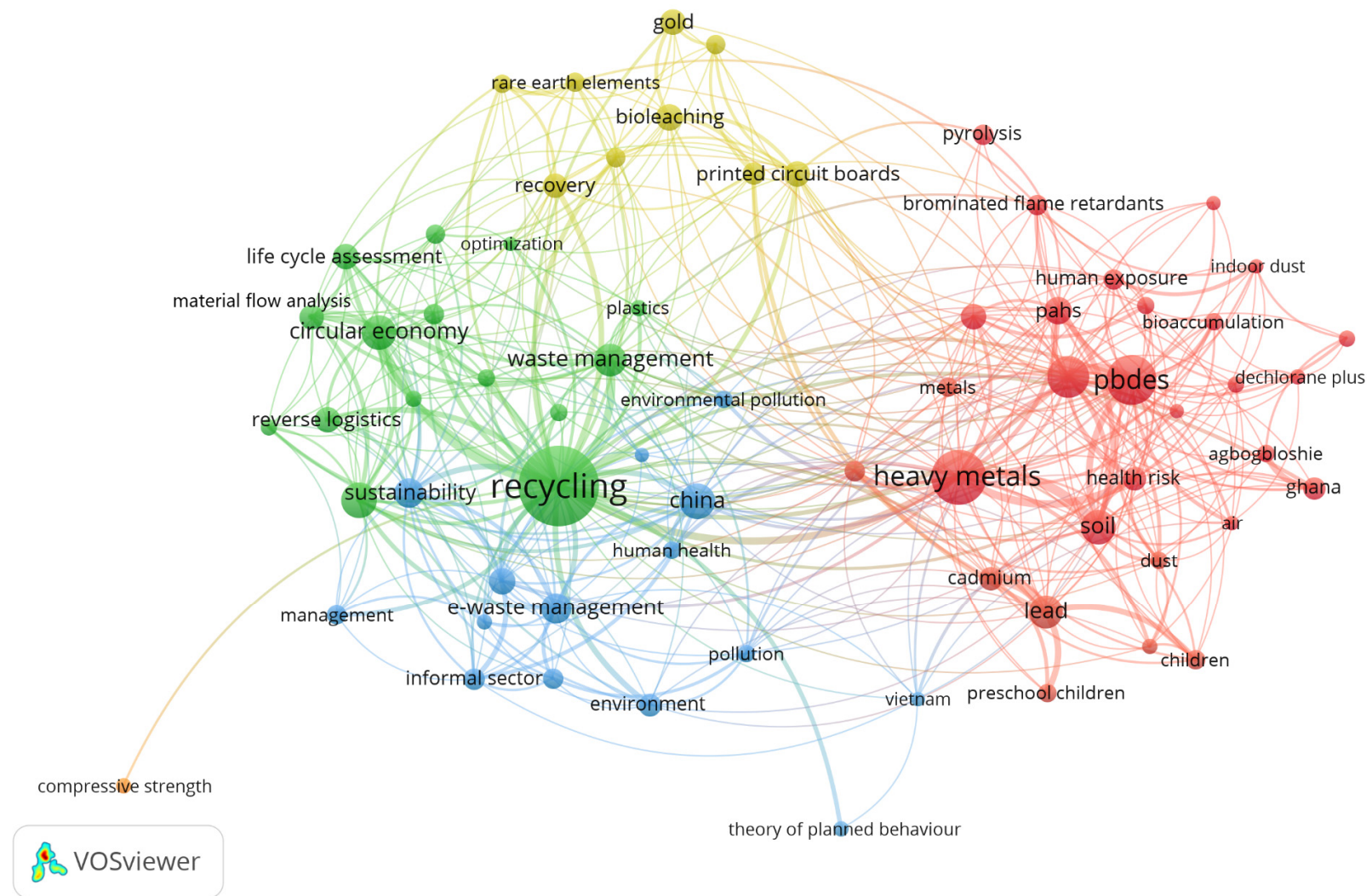


Figure 3. Keyword co-occurrence network map for peer-reviewed e-waste literature from 2010 to 2020. (pbdes = Polybrominated diphenyl ethers, pcbs = polychlorinated biphenyls, pahs=polycyclic aromatic hydrocarbons).

It should be noted that, among the 1835 studies that were considered, ‘circular economy’ appeared as a keyword only in 48 studies and ‘sustainability’ in 37 studies. Research related to policy and regulations contained a higher number of studies related to ‘EPR’ with 52 occurrences. As a concept that revolves around material recovery, ‘urban mining’ appeared as a keyword only in 12 articles. Although sustainable development goals (SDGs) came into action in 2015, surprisingly only two studies have included it in the keywords, suggesting that there are very few studies that have demonstrated a connection to SDGs. Since these are much broader umbrella terms, it is possible that these concepts could have been discussed in relation to the research topic in the body of the paper without being included as a keyword. However, one could argue that those would certainly appear as keywords if the concepts were a part of the essence of the research rather than a mere recognition. Consequently, this analysis reveals that, although there is an ample amount of research in all areas related to e-waste, the most prominent concepts related to sustainability appear much less frequently in e-waste research, implying that the connection is often overlooked.

3.2. Categorization of E-Waste Research According to the Research Focus

Although the keyword co-occurrence network generated a holistic view of e-waste literature and the main branches of research, an in-depth review of literature is needed to further understand focus areas in e-waste research and to identify existing gaps. The careful review of the selected 1835 studies resulted in identifying 10 major focus areas of e-waste research (Table 1). These categories were selected based on the primary research objective of the study. However, all studies that used MFA or LCA as a tool in assessing any aspects related to WEEE were grouped separately into two independent categories, regardless of their focus. Studies that could not be grouped into any of the first nine categories were labeled as ‘other’ in a 10th category.

Table 1. Categorization of literature on e-waste published between 2010 and 2020 based on the research focus.

	Research Focus	No of Articles	Description
1	Environmental or human health impacts	717	Ecological risk and human health implications resulting from improper handling and exposure to e-waste due to heavy metals and toxic chemicals
2	Recycling and recovery technologies	458	Methods, technologies, processes, and assessments of reuse and recycling of e-waste and material recovery aspects
3	E-waste generation estimates and general management	222	General management of e-waste, national/provincial-level estimations, predominant issues in collection, and overall management
4	Policy and regulations	105	Policies, legislations, and regulatory frameworks related to e-waste
5	Material/chemical characterization	77	Characterization of material and chemical composition of e-waste products
6	Associated social aspects	58	Social costs and benefits, consumer attitudes, perceptions, and behaviors related to e-waste
7	Circular economy aspects *	42	Studies that discussed CE concept as a main theme
8	Material Flow Analysis (MFA) *	33	Studies that utilized MFA as a tool in achieving the research objective
9	Life Cycle Assessment (LCA) *	31	Studies that utilized LCA as a tool in achieving the research objective
10	Other	89	Studies that could not be categorized into any of the other categories

* Research focus in some studies in these categories could overlap with other categories. However, considering the importance of identifying the focus in these specific areas, studies that included a significant contribution in circular economy aspects, MFA and LCA were categorized in independent categories.

Among the various topics, environmental and health impacts due to e-waste was the single most studied topic discussed by the researchers (717 articles) over the last decade. The analysis shows that recycling and recovery technologies (458 articles) and national/regional-level e-waste estimations and management aspects (222 articles) have also gained notable attention in WEEE research (Table 1).

However, for a holistic approach in managing the e-waste supply chain to ensure sustainability, understanding the quantities and identification of flow of materials along the entire supply chain is found to be essential, as reported by many previous studies [1,15,16,50]. Although MFA and LCA have been constantly acknowledged as valuable tools in waste management throughout literature [30,51], a comparatively smaller fraction of studies seemed to utilize those tools for e-waste research.

3.3. Application of MFA in E-Waste Research

As observed during the current literature review, 33 studies have used MFA as a tool to understand stocks and flows of e-waste in national/regional/product/element-level assessments. The scope or the level of assessment was identified through understanding the core topic of discussion and the system boundary, as previously carried out by [28]. If the research considered all e-waste flows in general within the national boundary, then the scope was considered to be 'National level'. However, some national level studies specifically focused on one or few electronic products as opposed to considering all WEEE flows. Such studies that focused on five or less products were identified as 'National level—Specific Products'. When an MFA is conducted in a city or on a provincial level, the scope was considered as 'Regional'. There was a single study [52] that considered e-waste in a group of universities, which is neither regional nor national and was grouped separately with two other studies [53,54] that focused on method development. Studies considering specific products and their element level flows were grouped as 'Element level'.

When using MFA for waste management research, it is also important to pay attention to whether the MFA model is a static or a dynamic model. A static MFA is a single-year evaluation of product and material flows with a fixed product lifespan, whereas a dynamic MFA is a multi-year evaluation of product and material flows with variable product lifespans [30]. The dynamic material flow model applies lifetime distribution of the static flow of a material to analyze and forecast its flow over time [55]. While the static model relies on linear correlation, the dynamic model is based on probabilistic lifetime distributions [30]. The present review attempted to identify whether each study used a static or a dynamic model in the respective MFA.

As depicted in Figure 4, a majority of the reviewed studies (20 studies) have considered a national-level assessment of e-waste stocks and flows. Among these, nine studies have assessed the flow of all WEEE in general without specifying products. A similar trend was observed in the review carried out by Islam & Huda (2019) which observed that 66% of all e-waste MFA studies are national-level assessments [28]. This could be due to the strict regulations that are being implemented by local and international bodies in recent times [28]. Most of these studies focused on issues such as e-waste generation estimation and material content in the generated e-waste stream. For example, Parajuly et al. (2017) studied the general quantities and the management system of household electronics in Denmark [1], Clarke et al. (2019) analyzed the WEEE management system in the United Kingdom over the period of 2010–2030 and the potential climate impacts from this [56], Mohammadi et al., (2021) estimated the stocks and flows of e-waste from 206 product types in five Caribbean islands [5], and Golev et al. (2016) analyzed and modeled the overall WEEE generation in Australia from 2010–2024 [57].

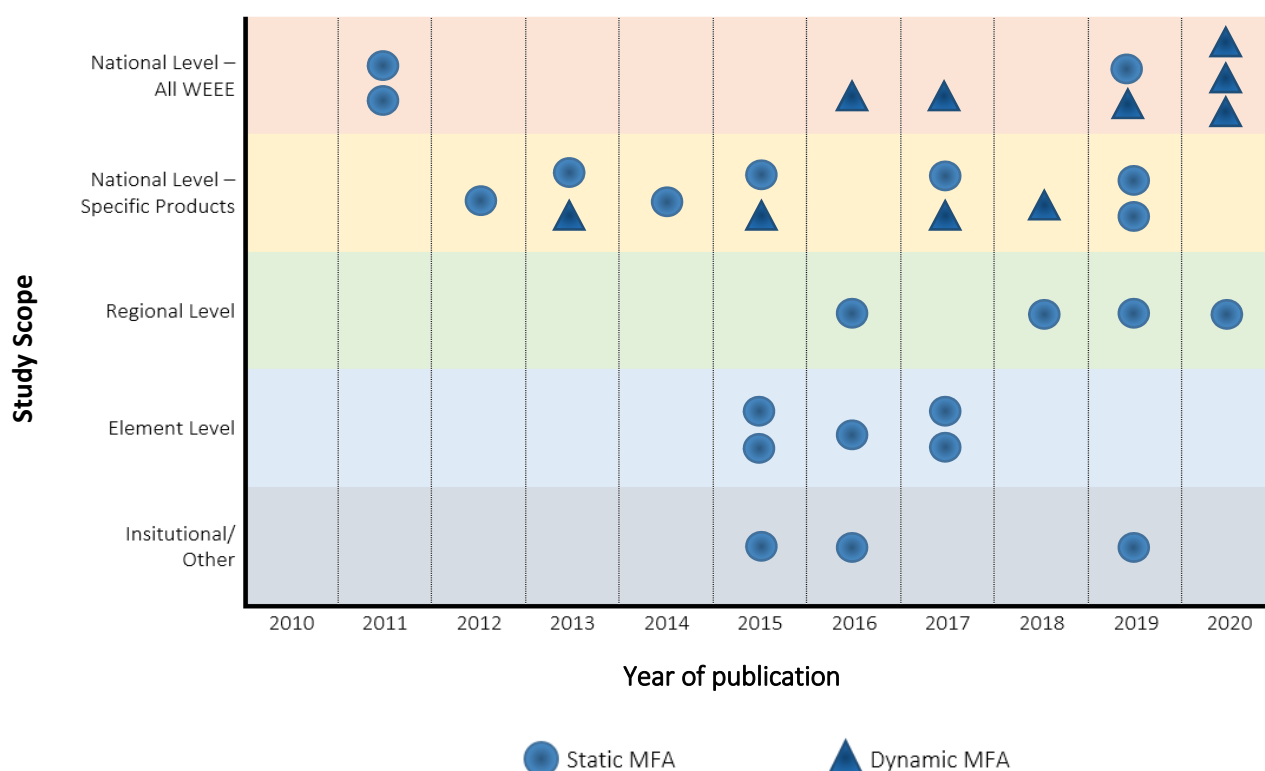


Figure 4. Overview of WEEE research that utilized MFA as a tool from 2010 onwards (Each circle/triangle stands for an individual study; shape denotes if the MFA used a static model or a dynamic model).

Analysis shows that 11 out of 20 studies that conducted national-level assessments focused on the stocks and flows of five or less specific products. According to the present review, personal computers, TVs and monitors, and mobile phones are the EEE product categories that have received significant attention in MFA e-waste research (Figure 5). Some studies considered only a single product (i.e., LCD (liquid-crystal-display) TVs in Vanegas et al. (2017), mobile phones in Babayemi et al. (2017), and CRT (cathode-ray tube) TVs in Gusukuma & Kahhat (2018)) [58–60], whereas some studies considered two or more products (i.e., refrigerators and computers in Yi et al. (2019) [61], computers and TVs in Lam et al. (2013) [62], and five products each in Andarani & Goto (2014) and Lau et al. (2013)) [63,64].

Products such as mobile phones, laptops and desktop computers contain high amounts of gold, silver, palladium, and other precious metals and rare earth elements, possibly attracting more attention from researchers. Islam & Huda (2019) also state that product specific channelization is a sophisticated issue that needs further consideration [28].

Besides national-level assessment, four studies have focused on the e-waste flows in cities or provinces in a more local context. Cao et al. (2016) used MFA to understand the generation, treatment, and public awareness of WEEE in Zhejiang Province, China [65]. Bahers & Kim (2018) used MFA to understand WEEE chain and extended producer responsibility (EPR) implementation in the regional and urban context through a case study in the Midi-Pyrénées Region and the Toulouse's urban area in France [66]. Gonda et al. (2019) highlights the importance of considering the regional spatial context for developing appropriate waste collection strategies by comparing the flows of EoL desktop computers in two neighboring regions in Belgium [67]. In another study in Cuenca, Ecuador by Davis (2020) developed and presented a replicable three-stage model to rapidly assess informal e-waste systems in developing countries [68].

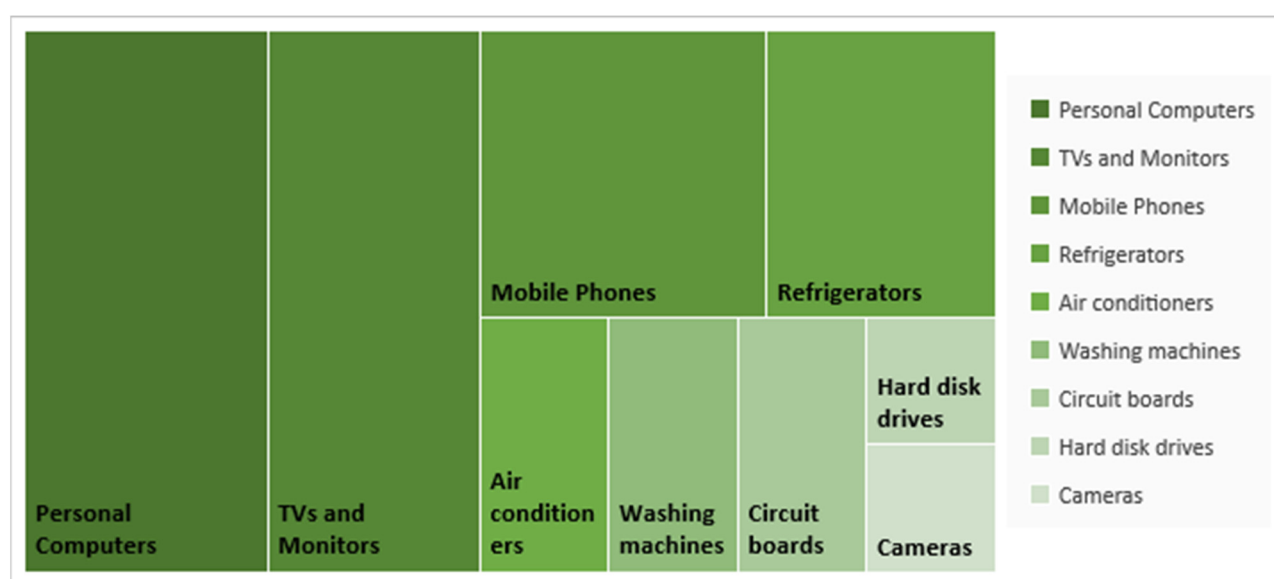


Figure 5. E-waste products considered in national-level MFA studies.

Due to the availability of precious metals and REEs, some researchers tend to focus on element-level assessments to understand the flows and stocks of specific elements. During the current review, five such studies were identified. Ueberschaar et al. (2017) focused on the recovery of Gallium from printed circuit boards and LEDs, whereas Sommer et al. (2015) estimated the flows of cobalt from batteries using a static MFA [68,69]. Moreover, through an MFA in an e-waste processing facility that processes computer hard disk drives containing neodymium-iron-boron (NdFeB) magnets Habib et al. (2015), it was highlighted there were inefficiencies in the recovery of REEs within the existing technology [15].

It was observed that both static and dynamic MFA methods were considered by the researchers along with numerous supplementary methods and research techniques. Out of the selected 33 studies, 10 studies used dynamic MFA model and 22 studies used static MFA. The remaining study was a literature review [28] of e-waste MFA studies. Most studies conducted the WEEE estimates using numerous complementary methods such as market supply surveys, secondary literature, and dynamic product lifespan models including the Weibull lifespan distribution function [1,50]. In addition, a combined approach of LCA and MFA was used in two studies [70,71].

It is also interesting to look at the geographical distribution of e-waste MFA research. It was evident that most of the studies were conducted in developed countries including four studies in US, three studies each in Germany and Belgium, and two studies each in Switzerland, India, Denmark, and Australia. This highlights that there are significant research gaps in relation to e-waste flows in developing countries which are usually the importers of e-waste.

3.4. Application of LCA in E-Waste Research

LCA is frequently referred to as one of the most suitable tools to assess environmental impacts associated with waste management and to compare the environmental performance of numerous waste management strategies including the handling and treatment of WEEE [33,35,72]. The complex nature of WEEE as a waste stream demands a holistic approach for the accurate assessment of associated environmental impacts, which is best supplied through LCA application making LCA an inherently valuable tool in WEEE research [73]. Furthermore, the last three decades have brought about strong methodological developments in the LCA approach, making it a more applicable and appealing tool [33,35].

The current literature review identified 31 studies that have used LCA as a tool to understand the life cycle environmental impacts associated with WEEE. Being the largest

producer, consumer, and recycler of electronics, China appears to be the country with the highest number of studies (eight studies) followed by Italy (four studies). However, it is worthwhile to note that nearly half of LCA studies related to WEEE are from the European region (15 studies), whereas only three developing countries (except for China) have at least a single study among the selected literature.

Since the application of LCA in WEEE management notably varied from one study to another, with the aim of presenting a clear understanding, this review categorized the selected articles into three broad categories, i.e., (1) Literature reviews, (2) Methodological frameworks for WEEE management, and (3) LCA of WEEE treatment methods/systems. The first category contains articles that presented systematic literature reviews of e-waste-related LCA studies. The second category includes studies that have presented novel methodological frameworks, models, and approaches for e-waste management using a life cycle approach. These studies may not have conducted a conventional LCA of WEEE product/products, but rather utilized the LCA tool to develop a management approach or a process. The studies that have conducted an LCA for selected WEEE product systems, treatment methods, or material recovery processes are included in the third category of the above classification. Categorization of the selected articles according to the published year, country, and the type of study is illustrated in Figure 6 below.

3.4.1. Category 1: Literature Reviews on LCA Studies Related to E-Waste

The current review identified two previous literature review articles which analyzed 61 [33] and 33 [34] LCA studies in WEEE management. Although both studies presented comprehensive overviews of WEEE literature associated with LCA, many recent studies that were published on or after 2017 were not included in these previous reviews. Moreover, instead of looking at the same aspects that were discussed in these previous review articles (e.g., research subjects and types of WEEE, methodological choices, research scale, impact category, etc.), the current review attempts to present a holistic view of the WEEE literature according to the life cycle stage considered in the system boundary of each study. This would enable the reader to understand which stage of the WEEE life cycle has more significant research gaps.

3.4.2. Category 2: Methodological Frameworks for WEEE Management/Treatment

A number of studies used the life cycle approach to develop and assess novel methodological frameworks or conceptual models for managing e-waste. de Souza et al. (2016) conducted an LCA of e-waste management system in the metropolitan region of Rio de Janeiro, Brazil where they considered the whole life cycle of e-waste, i.e., from e-waste collection to dismantling and recycling, and assessed the potential of implementing a reverse logistics system using a multi-criteria decision approach [74]. In a similar study, Song et al. (2017) presented a conceptual framework for the integrated management of WEEE for China from a life cycle perspective [75]. A few other studies [76,77] presented methodological improvements for LCA framework and its associated applications. For instance, Jaunich et al. (2020) presented a qualitative, holistic framework to systematically estimate life cycle impacts and costs associated with WEEE management and tested the framework using the state of Washington's e-waste management system [77]. It is important to note that, although the underlying aim of these studies was to contribute towards the methodological development of WEEE management in one way or another, there was quite a variation from one study to another due to their research approaches, making it difficult to compare.



Figure 6. Geographical and temporal distribution of three types of LCA studies related to e-waste.

3.4.3. Category 3: LCA of WEEE Treatment Systems/Methods

Evaluation of WEEE treatment systems or resource recovery methods was the most researched area in WEEE-related LCA studies according to the findings from the present study. Out of the 31 studies included in the present review, 24 studies fell into this category. Although there are multiple ways of analyzing the research content in these studies (i.e., based on the research subject, the research area and scope, and type of treatment, as illustrated in previous reviews [33,34] by Ismail & Hanafiah (2019) and Xue & Xu (2017)), this review focuses on taking a holistic view of the WEEE life cycle by assessing the system boundaries considered in each study. This approach assists in understanding which stages of the WEEE life cycle have been studied the most and where major research gaps in the life cycle exist.

While some studies focused on only a single stage of the WEEE life cycle (i.e., the collection or processing stage), some studies included several stages in their system boundary. For instance, Gamberini et al. (2010) studied the WEEE transportation network in the

north of Italy, considering only the collection stage [78]. Meanwhile, Solé et al. (2012) used LCA to improve the collection and recycling of small WEEE (electronic toys) where the system boundary included collection, pre-processing, and processing stages [79]. Similarly, two other studies [80,81] included collection, pre-processing, processing, and also disposal stages in their life cycle model. Except for the four studies mentioned above, all the other studies excluded the collection phase from their system boundary, making them either 'gate-to-gate' or 'gate-to-grave' LCAs. From these, four studies (Barletta et al., 2016; Li et al., 2019; Song et al., 2013; X. Song et al., 2017) [72,75,82,83] considered only the pre-processing and processing stages making them 'gate-to-gate' LCA, whereas two other studies [84,85] included the disposal stage as well by extending the system boundary to 'gate-to-grave'.

Interestingly, 10 of the selected studies considered only the processing stage, studying the recycling or resource recovery from e-waste. Among these, a few studies assessed the recycling of selected WEEE products such as washing machines, refrigerators, air conditioners and TVs [37], computers and TVs [86], and CRTs and PCBs [87], while [88] studied the recycling of e-waste plastics into sustainable filaments for 3D printing. Some studies focused on different metal recovery techniques from e-waste including hydrometallurgical treatment (i.e., [83,89]) and bioleaching [90]. There was only one study that specifically and solely looked at the disposal stage [91], which assessed life cycle environmental impacts from incineration of misplaced WEEE and other special wastes, mixed with residual household waste.

The study by Boldoczki et al. (2020) specifically stood out when considering life cycle stages included in its system boundary [92]. This was the only study that included the use of second-hand products into the system boundary. This study explored potential benefits of preparing for reuse (PfR) compared to other waste management options for four white goods (washing machine, refrigerator, range, and freezer) and four small electric devices (PC, printer, monitor, and laptop) using LCA in which the system boundary extended from preprocessing of the old product to the reuse of the new/second product. Findings of this study suggest that, although the reuse of small electric devices leads to significant reduction in environmental impacts since the use phase is less impactful in comparison to production, the reuse of products with a European energy efficient rating of D and C is not recommended.

3.5. Research Gaps in Existing Literature

Although it is not claiming to be an exhaustive content analysis, the present study demonstrates how MFA and LCA concepts have been applied to study numerous scopes related to different stages of the WEEE life cycle using a holistic approach. In relation to MFA studies, it was observed that the existing knowledge on the stocks and flows of e-waste in developing countries is extremely limited, especially in countries such as Nigeria, India, Indonesia, and Ghana which have become prominent e-waste importers. In order to discover the real efficiency of existing formal and informal e-waste recycling systems and to identify the potential for improvement, further research on e-waste stocks and flows in these developing countries is essential.

Moreover, when considering the element-level MFAs, there are still significant research opportunities to study the flow of precious elements such as gold across national/regional levels. Since precious metals can contribute significantly towards economic recovery potential, further research in this area could induce more attention and motivation towards a recycling economy.

Overall, most of the LCA studies were focused on assessing the recycling or resource recovery strategies relating only to pre-processing and processing stages. This reveals that, although there is an ample amount of knowledge regarding the impacts associated with numerous recycling and recovery technologies, there are also significant knowledge gaps on comparing these strategies with other management options, such as reuse and incineration for energy. Only a limited number of studies have attempted a holistic approach to evaluate WEEE management from collection to disposal or to the reuse of the second product. None

of the studies took into consideration the ‘prevention’ aspect into their system boundary, which is the top priority in the waste management hierarchy.

4. Conclusions

This systematic literature review provides a panoramic overview of the last decade of e-waste literature with an in-depth analysis of research that used MFA and LCA as a tool to analyze and assess generation, flows and stocks, and the environmental impacts regarding the handling and treatment of e-waste. E-waste is a growing area of research with significant potential in both developing and developed countries. At present, the majority of the e-waste research is focused on associated environmental and human health impacts and recycling/resource recovery technologies. Although there is a larger fraction of studies that have attempted to estimate the generation of e-waste using MFA, there are still major data gaps in relation to national-level estimates for both developed and developing nations. In addition, the MFA studies aimed at understanding the processing of e-waste at pre-processing and recycling facilities are limited. Moreover, MFA has already gained significant attention in e-waste research since it is capable of assisting in decision-making in relation to the management of complex waste streams such as e-waste. However, more research is required to deal with the assumptions being made while conducting e-waste MFAs due to data limitation. Similarly, LCA research regarding e-waste generation and handling is also sparse. This review emphasizes the need for more cradle-to-grave and cradle-to-cradle LCAs to obtain a more holistic understanding of e-waste life cycle in order to improve the current management practices and regulatory frameworks. Only a handful of studies have integrated MFA with LCA to quantify the associated environmental impacts. There is significant potential for future research for a combined MFA–LCA approach which would be inherently valuable in decision-making with respect to efficient management of finite raw materials. In addition, given that the circular economy is a fairly new field of research which is still on a continuous development, regardless of the many studies that were identified through our review, there is potential for further research on the application of the circular economy principles in e-waste management. Nevertheless, this review could be a starting point for any researcher interested in e-waste to gain a preliminary understanding of the major research themes and gaps, and also to apprehend the application of MFA and LCA in relation to numerous contexts related to e-waste.

Author Contributions: Conceptualization, supervision, funding acquisition, review and editing, K.H.; data collection, data curation, visualization and writing, S.V.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the NSERC Discovery project number RGPIN-2017-05218.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

EEE	electrical and electronic equipment
Mt	metric tonnes
MFA	material flow analysis
EoL	end-of-life
WEEE	waste electrical and electronic equipment
EU	European Union
REEs	rare earth elements
CRMs	critical raw materials
LCA	life cycle assessment
SLNA	systematic literature network analysis
LCD	liquid crystal display

CRT	cathode ray tube
PBDEs	polybrominated diphenyl ethers
PCBs	polychlorinated biphenyls

References

1. Parajuly, K.; Habib, K.; Liu, G. Waste electrical and electronic equipment (WEEE) in Denmark: Flows, quantities and management. *Resour. Conserv. Recycl.* **2017**, *123*, 85–92. [CrossRef]
2. Forti, V.; Baldé, C.P.; Kuehr, R.; Bel, G. *The Global E-Waste Monitor 2020: Quantities, Flows and the Circular Economy Potential*; United Nations University (UNU): Bonn, Germany; United Nations Institute for Training and Research (UNITAR): Bonn, Germany; International Telecommunication Union (ITU): Geneva, Switzerland; International Solid Waste Association (ISWA): Rotterdam, The Netherlands, 2020; p. 120. Available online: https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf (accessed on 19 September 2020).
3. Lau, W.K.-Y.; Chung, S.-S.; Zhang, C. A material flow analysis on current electrical and electronic waste disposal from Hong Kong households. *Waste Manag.* **2013**, *33*, 714–721. [CrossRef] [PubMed]
4. Kumar, A.; Holuszko, M. Electronic Waste and Existing Processing Routes: A Canadian Perspective. *Resources* **2016**, *5*, 35. [CrossRef]
5. Mohammadi, E.; Singh, S.J.; Habib, K. Electronic waste in the Caribbean: An impending environmental disaster or an opportunity for a circular economy? *Resour. Conserv. Recycl.* **2021**, *164*, 105106. [CrossRef]
6. Step Initiative. *Solving the E-Waste Problem (Step) White Paper: One Global Definition of E-Waste*; Step Initiative: Bonn, Germany; United Nations University: Bonn, Germany, 2014. Available online: <https://collections.unu.edu/view/UNU:6120#viewAttachments> (accessed on 19 September 2020).
7. Balde, C.P.; Forti, V.; Gray, V.; Kuher, R.; Stegmann, P. *Global E-Waste Monitor 2017*; United Nations University (UNU): Bonn, Germany; International Telecommunications Union (ITU): Geneva, Switzerland; International Solid Waste Association (ISWA): Vienna, Austria, 2017. Available online: https://collections.unu.edu/eserv/UNU:6341/Global-E-waste_Monitor_2017__electronic_single_pages_.pdf (accessed on 19 September 2020).
8. Forti, V.; Baldé, C.; Kuehr, R. *E-Waste Statistics Guidelines on Classification, Reporting and Indicators*, 2nd ed.; United Nations University: Bonn, Germany, 2018; ISBN 978-92-808-9067-9.
9. European Commission. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) Text with EEA relevance. *Off. J.* **2012**, *L197*, 38–71.
10. Robinson, B.H. E-waste: An assessment of global production and environmental impacts. *Sci. Total Environ.* **2009**, *408*, 183–191. [CrossRef]
11. The World Economic Forum. *A New Circular Vision for Electronics. Time for a Global Reboot*; 3 Cologny; United Nations E-Waste Coalition: Geneva, Switzerland, 2019; p. 23. Available online: http://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf (accessed on 20 September 2020).
12. Li, W.; Achal, V. Environmental and health impacts due to e-waste disposal in China—A review. *Sci. Total Environ.* **2020**, *737*, 139745. [CrossRef]
13. Yekeen, T.A.; Xu, X.; Zhang, Y.; Wu, Y.; Kim, S.; Reponen, T.; Dietrich, K.N.; Ho, S.; Chen, A.; Huo, X. Assessment of health risk of trace metal pollution in surface soil and road dust from e-waste recycling area in China. *Environ. Sci. Pollut. Res.* **2016**, *23*, 17511–17524. [CrossRef] [PubMed]
14. Grant, K.; Goldizen, F.C.; Sly, P.D.; Brune, M.-N.; Neira, M.; van den Berg, M.; Norman, R.E. Health consequences of exposure to e-waste: A systematic review. *Lancet Glob. Health* **2013**, *1*, e350–e361. [CrossRef]
15. Habib, K.; Parajuly, K.; Wenzel, H. Tracking the Flow of Resources in Electronic Waste—The Case of End-of-Life Computer Hard Disk Drives. *Environ. Sci. Technol.* **2015**, *49*, 12441–12449. [CrossRef]
16. Bakhiyi, B.; Gravel, S.; Ceballos, D.; Flynn, M.A.; Zayed, J. Has the question of e-waste opened a Pandora’s box? An overview of unpredictable issues and challenges. *Environ. Int.* **2018**, *110*, 173–192. [CrossRef]
17. Cucchiella, F.; D’Adamo, I.; Lenny Koh, S.C.; Rosa, P. Recycling of WEEEs: An economic assessment of present and future e-waste streams. *Renew. Sustain. Energy Rev.* **2015**, *51*, 263–272. [CrossRef]
18. Habib, K.; Hamelin, L.; Wenzel, H. A dynamic perspective of the geopolitical supply risk of metals. *J. Clean. Prod.* **2016**, *133*, 850–858. [CrossRef]
19. Charles, R.G.; Douglas, P.; Dowling, M.; Liversage, G.; Davies, M.L. Towards Increased Recovery of Critical Raw Materials from WEEE—evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. *Resour. Conserv. Recycl.* **2020**, *161*, 104923. [CrossRef]
20. Habib, K.; Wenzel, H. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. *J. Clean. Prod.* **2014**, *84*, 348–359. [CrossRef]
21. Gradin, K.T.; Poulakidou, S.; Björklund, A.; Luttrupp, C. Scrutinising the electric vehicle material backpack. *J. Clean. Prod.* **2018**, *172*, 1699–1710. [CrossRef]
22. Habib, K. Critical Resources in Clean Energy Technologies and Waste Flows. PhD Thesis, University of Southern Denmark, Odense, Denmark, 2015. Available online: https://findresearcher.sdu.dk:8443/ws/files/173370487/PhD_thesis_Komal_Habib.pdf (accessed on 19 September 2020).

23. Prodius, D.; Gandha, K.; Mudring, A.-V.; Nlebedim, I. Sustainable Urban Mining of Critical Elements from Magnet and Electronic Wastes. *ACS Sustain. Chem. Eng.* **2019**, *8*, 1455–1463. [CrossRef]
24. Sun, Z.; Cao, H.; Xiao, Y.; Sietsma, J.; Jin, W.; Agterhuis, H.; Yang, Y. Toward Sustainability for Recovery of Critical Metals from Electronic Waste: The Hydrochemistry Processes. *ACS Sustain. Chem. Eng.* **2017**, *5*, 21–40. [CrossRef]
25. Mirgorod, Y.A.; Borshch, N.A.; Borodina, V.G.; Yurkov, G.Y.; Timakov, D.I. Preparation of gold nanoparticles from the metal scrap. *Theor. Found. Chem. Eng.* **2014**, *48*, 487–492. [CrossRef]
26. Sethurajan, M.; Hullebusch, E.D.; van Fontana, D.; Akcil, A.; Deveci, H.; Batinic, B.; Leal, J.P.; Gasche, T.A.; Kucuker, M.A.; Kuchta, K.; et al. Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes—A review. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 212–275. [CrossRef]
27. Marra, A.; Cesaro, A.; Belgiorio, V. Recovery opportunities of valuable and critical elements from WEEE treatment residues by hydrometallurgical processes. *Environ. Sci. Pollut. Res. Int.* **2019**, *26*, 19897–19905. [CrossRef]
28. Islam, M.T.; Huda, N. Material flow analysis (MFA) as a strategic tool in E-waste management: Applications, trends and future directions. *J. Environ. Manag.* **2019**, *244*, 344–361. [CrossRef]
29. Kiddee, P.; Naidu, R.; Wong, M.H. Electronic waste management approaches: An overview. *Waste Manag.* **2013**, *33*, 1237–1250. [CrossRef]
30. Brunner, P.H.; Rechberger, H. Practical Handbook of Material Flow Analysis. In *Advanced Methods in Resource and Waste Management*; CRC, Lewis: Boca Raton, FL, USA, 2004; ISBN 978-1-56670-604-9.
31. Cordova-Pizarro, D.; Aguilar-Barajas, I.; Romero, D.; Rodriguez, C.A. Circular Economy in the Electronic Products Sector: Material Flow Analysis and Economic Impact of Cellphone E-Waste in Mexico. *Sustainability* **2019**, *11*, 1361. [CrossRef]
32. Althaf, S.; Babbitt, C.W.; Chen, R. Forecasting electronic waste flows for effective circular economy planning. *Resour. Conserv. Recycl.* **2019**, *151*, 104362. [CrossRef]
33. Ismail, H.; Hanafiah, M.M. An overview of LCA application in WEEE management: Current practices, progress and challenges. *J. Clean. Prod.* **2019**, *232*, 79–93. [CrossRef]
34. Xue, M.; Xu, Z. Application of Life Cycle Assessment on Electronic Waste Management: A Review. *Environ. Manag.* **2017**, *59*, 693–707. [CrossRef] [PubMed]
35. Finnveden, G.; Björklund, A.; Moberg, Å.; Ekvall, T.; Moberg, Å. Environmental and economic assessment methods for waste management decision-support: Possibilities and limitations. *Waste Manag. Res.* **2007**, *25*, 263–269. [CrossRef]
36. Ikhlail, M. Environmental impacts and benefits of state-of-the-art technologies for E-waste management. *Waste Manag.* **2017**, *68*, 458–474. [CrossRef]
37. Menikpura, S.N.M.; Santo, A.; Hotta, Y. Assessing the climate co-benefits from Waste Electrical and Electronic Equipment (WEEE) recycling in Japan. *J. Clean. Prod.* **2014**, *74*, 183–190. [CrossRef]
38. Pérez-Belis, V.; Bovea, M.; Ibáñez-Forés, V. An in-depth literature review of the waste electrical and electronic equipment context: Trends and evolution. *Waste Manag. Res.* **2015**, *33*, 3–29. [CrossRef] [PubMed]
39. Ismail, H.; Hanafiah, M.M. A review of sustainable e-waste generation and management: Present and future perspectives. *J. Environ. Manag.* **2020**, *264*, 110495. [CrossRef] [PubMed]
40. Khitous, F.; Strozzi, F.; Urbinati, A.; Alberti, F. A Systematic Literature Network Analysis of Existing Themes and Emerging Research Trends in Circular Economy. *Sustainability* **2020**, *12*, 1633. [CrossRef]
41. Bamel, U.K.; Pandey, R.; Gupta, A. Safety climate: Systematic literature network analysis of 38 years (1980–2018) of research. *Accid. Anal. Prev.* **2020**, *135*, 105387. [CrossRef] [PubMed]
42. van Eck, N.J.; Waltman, L. VOSviewer-Visualizing Scientific Landscapes [Software]. Available online: <https://www.vosviewer.com/> (accessed on 15 February 2021).
43. van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
44. Ottoni, M.; Dias, P.; Xavier, L.H. A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil. *J. Clean. Prod.* **2020**, *261*, 120990. [CrossRef]
45. Singh, A.; Panchal, R.; Naik, M. Circular economy potential of e-waste collectors, dismantlers, and recyclers of Maharashtra: A case study. *Environ. Sci. Pollut. Res.* **2020**, *27*, 22081–22099. [CrossRef]
46. Nowakowski, P.; Mrówczyńska, B. Towards sustainable WEEE collection and transportation methods in circular economy—Comparative study for rural and urban settlements. *Resour. Conserv. Recycl.* **2018**, *135*, 93–107. [CrossRef]
47. Wagner, F.; Peeters, J.R.; De Keyser, J.; Janssens, K.; Duflou, J.R.; Dewulf, W. Towards a more circular economy for WEEE plastics—Part A: Development of innovative recycling strategies. *Waste Manag.* **2019**, *100*, 269–277. [CrossRef]
48. Corsini, F.; Gusmerotti, N.; Frey, M. Consumer's Circular Behaviors in Relation to the Purchase, Extension of Life, and End of Life Management of Electrical and Electronic Products: A Review. *Sustainability* **2020**, *12*, 443. [CrossRef]
49. Habib, K. A product classification approach to optimize circularity of critical resources—The case of NdFeB magnets. *J. Clean. Prod.* **2019**, *230*, 90–97. [CrossRef]
50. Islam, M.T.; Huda, N. Reverse logistics and closed-loop supply chain of Waste Electrical and Electronic Equipment (WEEE)/E-waste: A comprehensive literature review. *Resour. Conserv. Recycl.* **2018**, *137*, 48–75. [CrossRef]
51. Allesch, A.; Brunner, P.H. Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria. *Environ. Sci. Technol.* **2017**, *51*, 540–551. [CrossRef]

52. Agamuthu, P.; Kasapo, P.; Mohd Nordin, N.A. E-waste flow among selected institutions of higher learning using material flow analysis model. *Resour. Conserv. Recycl.* **2015**, *105*, 177–185. [\[CrossRef\]](#)
53. Althaf, S.; Babbitt, C.W.; Chen, R. The evolution of consumer electronic waste in the United States. *J. Ind. Ecol.* **2020**. [\[CrossRef\]](#)
54. Yedla, S. Development of a methodology for electronic waste estimation: A material flow analysis-based SYE-Waste Model. *Waste Manag. Res.* **2016**, *34*, 81–86. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Park, J.; Hong, S.; Kim, I.; Lee, J.; Hur, T. Dynamic material flow analysis of steel resources in Korea. *Resour. Conserv. Recycl.* **2011**, *55*, 456–462. [\[CrossRef\]](#)
56. Clarke, C.; Williams, I.D.; Turner, D.A. Evaluating the carbon footprint of WEEE management in the UK. *Resour. Conserv. Recycl.* **2019**, *141*, 465–473. [\[CrossRef\]](#)
57. Golev, A.; Schmeda-Lopez, D.R.; Smart, S.K.; Corder, G.D.; McFarland, E.W. Where next on e-waste in Australia? *Waste Manag.* **2016**, *58*, 348–358. [\[CrossRef\]](#)
58. Vanegas, P.; Peeters, J.R.; Cattrysse, D.; Dewulf, W.; Duflou, J.R. Improvement potential of today's WEEE recycling performance: The case of LCD TVs in Belgium. *Front. Environ. Sci. Eng.* **2017**, *11*, 13. [\[CrossRef\]](#)
59. Babayemi, J.O.; Osibanjo, O.; Weber, R. Material and substance flow analysis of mobile phones in Nigeria: A step for progressing e-waste management strategy. *J. Mater. Cycles Waste Manag.* **2017**, *19*, 731–742. [\[CrossRef\]](#)
60. Gusukuma, M.; Kahhat, R. Electronic waste after a digital TV transition: Material flows and stocks. *Resour. Conserv. Recycl.* **2018**, *138*, 142–150. [\[CrossRef\]](#)
61. Yi, S.; Lee, H.; Lee, J.; Kim, W. Upcycling strategies for waste electronic and electrical equipment based on material flow analysis. *Environ. Eng. Res.* **2019**, *24*, 74–81. [\[CrossRef\]](#)
62. Lam, C.W.; Lim, S.-R.; Schoenung, J.M. Linking Material Flow Analysis with Environmental Impact Potential. *J. Ind. Ecol.* **2013**, *17*, 299–309. [\[CrossRef\]](#)
63. Andarani, P.; Goto, N. Potential e-waste generated from households in Indonesia using material flow analysis. *J. Mater. Cycles Waste Manag.* **2014**, *16*, 306–320. [\[CrossRef\]](#)
64. Cao, J.; Chen, Y.; Shi, B.; Lu, B.; Zhang, X.; Ye, X.; Zhai, G.; Zhu, C.; Zhou, G. WEEE recycling in Zhejiang Province, China: Generation, treatment, and public awareness. *J. Clean. Prod.* **2016**, *127*, 311–324. [\[CrossRef\]](#)
65. Bahers, J.-B.; Kim, J. Regional approach of waste electrical and electronic equipment (WEEE) management in France. *Resour. Conserv. Recycl.* **2018**, *129*, 45–55. [\[CrossRef\]](#)
66. Gonda, L.; D'Ans, P.; Degrez, M. A comparative assessment of WEEE collection in an urban and rural context: Case study on desktop computers in Belgium. *Resour. Conserv. Recycl.* **2019**, *142*, 131–142. [\[CrossRef\]](#)
67. Davis, J.-M. A model to rapidly assess informal electronic waste systems. *Waste Manag. Res.* **2020**, *39*, 101–107. [\[CrossRef\]](#)
68. Ueberschaar, M.; Geiping, J.; Zamzow, M.; Flamme, S.; Rotter, V.S. Assessment of element-specific recycling efficiency in WEEE pre-processing. *Resour. Conserv. Recycl.* **2017**, *124*, 25–41. [\[CrossRef\]](#)
69. Sommer, P.; Rotter, V.S.; Ueberschaar, M. Battery related cobalt and REE flows in WEEE treatment. *Waste Manag.* **2015**, *45*, 298–305. [\[CrossRef\]](#) [\[PubMed\]](#)
70. De Meester, S.; Nachtergaele, P.; Debaveye, S.; Vos, P.; Dewulf, J. Using material flow analysis and life cycle assessment in decision support: A case study on WEEE valorization in Belgium. *Resour. Conserv. Recycl.* **2019**, *142*, 1–9. [\[CrossRef\]](#)
71. Wäger, P.A.; Hirsch, R.; Eugster, M. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up. *Sci. Total Environ.* **2011**, *409*, 1746–1756. [\[CrossRef\]](#)
72. Song, Q.; Wang, Z.; Li, J. Sustainability evaluation of e-waste treatment based on emergy analysis and the LCA method: A case study of a trial project in Macau. *Ecol. Indic.* **2013**, *30*, 138–147. [\[CrossRef\]](#)
73. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.-P.; Suh, S.; Weidema, B.; Pennington, D. Life Cycle Assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications. *Environ. Int.* **2004**, *30*, 701–720. [\[CrossRef\]](#)
74. deSouza, R.G.; Clímaco, J.C.N.; Sant'Anna, A.P.; Rocha, T.B.; doValle, R.D.A.B.; Quelhas, O.L.G. Sustainability assessment and prioritisation of e-waste management options in Brazil. *Waste Manag.* **2016**, *57*, 46–56. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Song, X.; Wang, J.; Yang, J.; Lu, B. An updated review and conceptual model for optimizing WEEE management in China from a life cycle perspective. *Front. Environ. Sci. Eng.* **2017**, *11*, 3. [\[CrossRef\]](#)
76. Jaunich, M.K.; DeCarolis, J.; Handfield, R.; Kemahlioglu-Ziya, E.; Ranjithan, S.R.; Moheb-Alizadeh, H. Life-cycle modeling framework for electronic waste recovery and recycling processes. *Resour. Conserv. Recycl.* **2020**, *161*, 104841. [\[CrossRef\]](#)
77. Rigamonti, L.; Falbo, A.; Zampori, L.; Sala, S. Supporting a transition towards sustainable circular economy: Sensitivity analysis for the interpretation of LCA for the recovery of electric and electronic waste. *Int. J. Life Cycle Assess.* **2017**, *22*, 1278–1287. [\[CrossRef\]](#)
78. Gamberini, R.; Gebennini, E.; Manzini, R.; Ziveri, A. On the integration of planning and environmental impact assessment for a WEEE transportation network—A case study. *Resour. Conserv. Recycl.* **2010**, *54*, 937–951. [\[CrossRef\]](#)
79. Solé, M.; Watson, J.; Puig, R.; Fullana-i-Palmer, P. Proposal of a new model to improve the collection of small WEEE: A pilot project for the recovery and recycling of toys. *Waste Manag. Res.* **2012**, *30*, 1208–1212. [\[CrossRef\]](#) [\[PubMed\]](#)
80. Baxter, J.; Lyng, K.-A.; Askham, C.; Hanssen, O.J. High-quality collection and disposal of WEEE: Environmental impacts and resultant issues. *Waste Manag.* **2016**, *57*, 17–26. [\[CrossRef\]](#)

-
81. Lu, B.; Song, X.; Yang, J.; Yang, D. Comparison on End-of-Life strategies of WEEE in China based on LCA. *Front. Environ. Sci. Eng.* **2017**, *11*, 7. [[CrossRef](#)]
 82. Barletta, I.; Larborn, J.; Mani, M.; Johansson, B. Towards an Assessment Methodology to Support Decision Making for Sustainable Electronic Waste Management Systems: Automatic Sorting Technology. *Sustainability* **2016**, *8*, 84. [[CrossRef](#)]
 83. Li, Z.; Diaz, L.A.; Yang, Z.; Jin, H.; Lister, T.E.; Vahidi, E.; Zhao, F. Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. *Resour. Conserv. Recycl.* **2019**, *149*, 20–30. [[CrossRef](#)]
 84. Lu, B.; Liu, J.; Yang, J.; Li, B. The environmental impact of technology innovation on WEEE management by Multi-Life Cycle Assessment. *J. Clean. Prod.* **2015**, *89*, 148–158. [[CrossRef](#)]
 85. Shaikh, S.; Thomas, K.; Zuhair, S.; Magalini, F. A cost-benefit analysis of the downstream impacts of e-waste recycling in Pakistan. *Waste Manag.* **2020**, *118*, 302–312. [[CrossRef](#)]
 86. Hong, J.; Shi, W.; Wang, Y.; Chen, W.; Li, X. Life cycle assessment of electronic waste treatment. *Waste Manag.* **2015**, *38*, 357–365. [[CrossRef](#)]
 87. Song, Q.; Zeng, X.; Li, J.; Duan, H.; Yuan, W. Environmental risk assessment of CRT and PCB workshops in a mobile e-waste recycling plant. *Environ. Sci. Pollut. Res. Int.* **2015**, *22*, 12366–12373. [[CrossRef](#)]
 88. Gaikwad, V.; Ghose, A.; Cholake, S.; Rawal, A.; Iwato, M.; Sahajwalla, V. Transformation of E-Waste Plastics into Sustainable Filaments for 3D Printing. *ACS Sustain. Chem. Eng.* **2018**, *6*, 14432–14440. [[CrossRef](#)]
 89. Iannicelli-Zubiani, E.M.; Giani, M.I.; Recanati, F.; Dotelli, G.; Puricelli, S.; Cristiani, C. Environmental impacts of a hydrometallurgical process for electronic waste treatment: A life cycle assessment case study. *J. Clean. Prod.* **2017**, *140*, 1204–1216. [[CrossRef](#)]
 90. Villares, M.; Işildar, A.; Mendoza Beltran, A.; Guinee, J. Applying an ex-ante life cycle perspective to metal recovery from e-waste using bioleaching. *J. Clean. Prod.* **2016**, *129*, 315–328. [[CrossRef](#)]
 91. Bigum, M.; Damgaard, A.; Scheutz, C.; Christensen, T.H. Environmental impacts and resource losses of incinerating misplaced household special wastes (WEEE, batteries, ink cartridges and cables). *Resour. Conserv. Recycl.* **2017**, *122*, 251–260. [[CrossRef](#)]
 92. Boldoczki, S.; Thorenz, A.; Tuma, A. The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany. *J. Clean. Prod.* **2020**, *252*, 119736. [[CrossRef](#)]